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PATENT APPLICATION

**UNITED STATES PATENT APPLICATION**

of

**Randy Hoffman**

for

**INORGANIC ELECTROLUMINESCENT DEVICE WITH CONTROLLED HOLE  
AND ELECTRON INJECTION**

TO THE COMMISSIONER OF PATENTS AND TRADEMARKS:

Your petitioner, **Randy Hoffman, citizen of the United States**, whose residence and postal mailing address is **219 SW 7th Street, Corvallis, OR 97333**, prays that letters patent may be granted to him as the inventor of a **INORGANIC ELECTROLUMINESCENT DEVICE WITH CONTROLLED HOLE AND ELECTRON INJECTION** as set forth in the following specification.

## INORGANIC ELECTROLUMINESCENT DEVICE WITH CONTROLLED HOLE AND ELECTRON INJECTION

### BACKGROUND OF THE INVENTION

[0001] Electroluminescent (EL) devices hold the promise of providing a display technology superior to the cathode ray tube and liquid crystal displays in widespread use today. Although various EL devices have been known for years, development of EL displays has been relatively slow due to a number of technical challenges.

[0002] At least two different types of EL devices are known: tunneling EL devices and diode junction EL devices. Tunneling EL devices may be fabricated by placing a phosphor material between two electrodes and placing an insulating layer between one or both electrodes and the phosphor. Injection of carriers is accomplished by imposing a high voltage across the phosphor that enables tunneling of carriers, typically electrons, through the insulating layer. The high electric field accelerates the injected carriers that then interact with luminance centers within the phosphor resulting in emission of visible light.

[0003] Diode junction EL devices, on the other hand, are fabricated by doping the phosphor material to create a PN junction. Under forward bias conditions, holes and electrons recombine near the PN junction to emit light.

[0004] Both types of EL devices suffer from a number of problems, however, due to the high voltages required to inject carriers. High voltages in the phosphor region accelerate carriers to high velocities, such that many of the charge carriers pass quickly through the phosphor region without recombining or interacting with the luminance centers of the phosphor. The charge carriers do not contribute to electroluminescence, and hence, they create a wasteful leakage current, which lowers efficiency. Furthermore, high voltages can lead to catastrophic breakdown of the insulating layers or phosphor, destroying the device.

[0005] Fabrication of diode junction EL devices is also difficult since doping of most inorganic phosphors is difficult to achieve, limiting the choice of inorganic phosphor materials suitable for commercial EL devices. For those

phosphors that can be doped, doping is typically limited to one carrier type, thus, limiting the efficiency of the devices.

5       **[0006]** Although the lower carrier mobility of organic phosphors can result in improved functionality, organic phosphors present a whole new set of difficulties. Organic phosphors tend to be highly chemically reactive and can rapidly degrade if exposed to the environment. The high reactivity of organic phosphors also limits the choices of materials that can be used for electrodes, since many organic phosphors will readily combine with the metal in the electrode, resulting in degradation of the device performance. Practical devices  
10       using an organic phosphor require special chemical isolation layers at the junctions and careful packaging to manage the reactivity of the phosphor. Achieving long life with organic phosphors has also proven difficult.

#### SUMMARY OF THE INVENTION

15       **[0007]** It has been recognized that it would be advantageous to develop an efficient electroluminescent device based on hole and electron injection and recombination in an inorganic phosphor.

20       **[0008]** One embodiment of the present invention includes an electroluminescent device configured to produce electroluminescence from the recombination of injected holes and electrons in an inorganic phosphor. The electroluminescent device includes a controllable hole injection structure in contact with the inorganic phosphor. A first applied control voltage controls a rate of hole injection into the inorganic phosphor. The embodiment of an electroluminescent device also includes a controllable electron injection structure  
25       in contact with the inorganic phosphor and separated from the controllable hole injection structure by a recombination region of the inorganic phosphor. A second applied voltage controls the rate of electron injection into the inorganic phosphor.

30       **[0009]** Additional features and advantages of the invention will be apparent from the detailed description which follows, taken in conjunction with the accompanying drawings, which together illustrate, by way of example, features of the invention.

### BRIEF DESCRIPTION OF THE DRAWINGS

[0010] FIG. 1 is a schematic view of an electroluminescent device in accordance with an embodiment of the present invention;

5 [0011] FIG. 2 is a sectional view of an electroluminescent device in accordance with another embodiment of the present invention;

[0012] FIG. 3 is an energy band diagram for the electroluminescent device of FIG. 2 with no applied voltage;

10 [0013] FIG. 4 is an energy band diagram for the electroluminescent device of FIG. 2 with sufficient applied voltage to cause electroluminescence;

[0014] FIG. 5 is a sectional view of an electroluminescent device in accordance with another embodiment of the present invention;

[0015] FIG. 6 is a sectional view of an electroluminescent device in accordance with another embodiment of the present invention;

15 [0016] FIG. 7 is a schematic diagram of a display implemented using the electroluminescent device of FIG. 1 in accordance with another embodiment of the present invention; and

[0017] FIG. 8 is a flow chart of a method of fabrication of an electroluminescent device in accordance with an embodiment of the present invention.

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### DETAILED DESCRIPTION

[0018] Reference will now be made to the exemplary embodiments illustrated in the drawings, and specific language will be used herein to describe the same. It will nevertheless be understood that no limitation of the scope of the invention is thereby intended. Alterations and further modifications of the inventive features illustrated herein, and additional applications of the principles of the inventions as illustrated herein, which would occur to one skilled in the relevant art and having possession of this disclosure, are to be considered within the scope of the invention.

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[0019] An embodiment of an electroluminescent device is illustrated in FIG. 1, indicated generally at 10, in accordance with an embodiment of the

present invention. The electroluminescent device 10 includes an inorganic phosphor 12 configured to produce electroluminescence from the recombination of injected holes and electrons. Exemplary materials which may be used for the inorganic phosphor 12 include ZnS, SrS, BaS, CaS, ZnO, ZnSe, GaN, and GaP.

5           **[0020]** The electroluminescent device 10 also includes a controllable hole injection structure 14 and a controllable electron injection structure 16 each separated from each other and in contact with the inorganic phosphor 12. A hole injection control voltage 18 may be applied across the hole injection structure 14 using the anode contact 24 and the hole injection control gate contact 34 to  
10 create a sufficiently high E-field intensity within the hole injection structure 14 to enable the injection of holes from the anode contact 24. The hole injection control voltage 18 may be varied to control the rate of hole injection. An electron injection control voltage 20 may be applied across the electron injection structure 16 using the cathode contact 26 and the electron injection control gate contact 36  
15 to create a sufficiently high E-field intensity within the electron injection structure 16 to enable the injection of electrons. The electron injection control voltage 20 may be varied to control the rate of electron injection. High E-field intensities created by the control voltages 18, 20 are substantially contained within the injection structures 14, 16 in part because of the separation of the injection  
20 structures 14, 16 from each other and in part because of the separation of the injection structures 14, 16 from a recombination region 13 of the inorganic phosphor 12.

**[0021]** An electroluminescence voltage 22 may be applied between the hole injection structure 14 and the electron injection structure 16 and, thus,  
25 across the inorganic phosphor 12. As the electroluminescence voltage 22 is made increasingly positive, the resulting E-field across the inorganic phosphor 12 will draw holes and electrons away from the injection structures 14, 16, respectively and toward each other, where they will radiatively recombine in the recombination region 13 of the inorganic phosphor 12, producing  
30 electroluminescence. Relatively low electroluminescence voltage 22 can be used to produce appreciable electroluminescence because the flow of carriers is a bulk drift current. By avoiding high E-fields in the recombination region 13, the

velocity of carriers is kept relatively low, thus reducing the number of carriers that pass through the inorganic phosphor 12 without recombining. The efficiency of the electroluminescent device 10 is thus enhanced.

**[0022]** FIG. 2 provides further detail of an electroluminescent device, indicated generally at 100, in accordance with another embodiment of the present invention. The electroluminescent device 100 includes a controllable hole injection structure 14, including a hole injection region 142 in contact with the inorganic phosphor 12. The controllable hole injection structure 14 also includes a field effect gate structure including a hole injection control gate 144 and a hole injection control gate insulator layer 146. The hole injection control gate 144 is located opposite the hole injection region 142, but separated from the inorganic phosphor 12 by the hole injection control gate insulator layer 146.

**[0023]** The electroluminescent device 100 may further include a controllable electron injection structure 16 including an electron injection region 162 in contact with the inorganic phosphor 12. The controllable electron injection structure 16 also includes a field effect gate structure including an electron injection control gate 164 and an electron injection control gate insulator layer 166. The electron injection control gate 164 is located opposite the electron-injection region 162, but separated from the inorganic phosphor 12 by the electron injection control gate insulator layer 166. Although the hole injection control gate insulator layer 146 and electron injection control gate insulator layer 166 are shown as two separate regions, they may be formed as one continuous layer according to another embodiment of an electroluminescent device in accordance with the present invention.

**[0024]** Operation of the electroluminescent device 100 can be understood by referring to the energy band diagrams of FIGS. 3 and 4. FIG. 3 illustrates an energy band diagram for the controllable hole injection structure 14 of the electroluminescent device 100 taken along a cross section from point A to point B (see FIG. 2). In FIG. 3, the hole injection control voltage 18 is assumed to be set to zero volts.  $E_{vac}$  represents the vacuum energy level, and  $E_F$  represents the Fermi energy level of the hole injection region 142 and the hole injection control gate 144. In FIG. 3, for illustration purposes only, it has been

assumed the hole injection region 142 and the hole injection control gate 144 have identical work functions. The hole injection region 142 and hole injection control gate 144 may be fabricated of different materials. The symbol,  $\phi_h$ , represents the work function of the hole injection region 142.  $E_{GP}$  is the energy bandgap of the inorganic phosphor 12, corresponding to the difference between the inorganic phosphor valence band maximum energy level,  $E_{VP}$ , and conduction band minimum energy level,  $E_{CP}$ .  $E_{GI}$  is the energy bandgap of the hole injection control gate insulator layer 146, i.e. the difference between the insulator layer valence band maximum energy level,  $E_{VI}$ , and conduction band minimum energy level  $E_{CI}$ .

**[0025]** The hole injection barrier  $E_F - E_{VP}$  may be minimized, by choosing a high work function metal for the hole injection region 142, according to embodiments of the present invention. For example, suitable high work function metals for embodiments of the present invention include Au, Pt, Pd, and Ni. In alternative embodiments of the present invention, the hole injection region 142 may be fabricated from a p-type doped semiconductor, optionally a wide bandgap semiconductor. A wide bandgap semiconductor may result in a lower hole injection barrier, particularly if it has a high electron affinity (difference between conduction band minimum and vacuum level). Examples of suitable semiconductors for embodiments of the present invention include NiO,  $Cu_2O$ ,  $Co_3O_4$ ,  $SrCu_2O_2$ ,  $BaCu_2S_2$ , LaCuOS, GaN, and the class of materials  $CuMO_2$ , where M=Al, Y, Sc, Cr, In, or Ga.

**[0026]** The hole injection barrier remains relatively high (for example, approximately 1 eV) for practical choices of a high work function metal and inorganic phosphor. The hole injection barrier may be overcome by the hole injection control voltage 18.

**[0027]** FIG. 4 illustrates an energy band diagram for an embodiment of the controllable hole injection structure 14 of electroluminescent device 100 for the case where the hole injection control voltage 18 is set sufficiently high to overcome the hole injection barrier. Holes tunnel through the triangular energy barrier from the hole injection region 142 into the inorganic phosphor 12. Holes entering the inorganic phosphor 12 will be swept to the boundary between the

inorganic phosphor 12 and the hole injection control gate insulator 146. Holes cannot enter the hole injection control gate insulator 146 due to a large barrier ( $E_F - E_{VI}$ ) and, hence, a hole accumulation layer 124 (see FIG. 2) will form at the surface of the phosphor region directly adjacent to the hole injection control gate insulator 146.

**[0028]** Operation of the controllable electron injection structure 16 follows similar principles to those illustrated above and will be readily apparent to one of ordinary skill in the art and, thus, will not be further elaborated herein. Electrons are injected from the electron injection region 162 into the inorganic phosphor 12 and form an electron accumulation layer 126 at the surface of the phosphor region directly adjacent to the electron injection control gate insulator 166.

**[0029]** Electron injection according to embodiments of the present invention may be facilitated by the choice of a low work function metal for the electron injection region 162 (see FIG. 2), minimizing the electron injection barrier. Examples of suitable low work function metals consistent with embodiments of the present invention include Ca, Li, K, Na, Mg, Sc, In, Al, Ti, Ta, and Ag. According to alternative embodiments of the present invention, the electron injection region 162 may be fabricated from an n-type doped semiconductor. Examples of suitable n-type doped semiconductors include ZnO, SnO<sub>2</sub>, In<sub>2</sub>O<sub>3</sub>, GaN consistent with embodiments of the present invention. Because electron injection is generally easier than hole injection, there is more flexibility in the choice of a suitable electron injector than in the choice of a suitable hole injector.

**[0030]** Imposition of the electroluminescence voltage 22 will cause drift of holes and electrons within the inorganic phosphor 12 away from the accumulation layers 124, 126 toward the recombination region 13, where they may recombine, producing electroluminescence. Control of the electroluminescence intensity may thus be obtained by variation of the electroluminescence voltage 22. According to alternative embodiments of the present invention, control of electroluminescence intensity may be obtained by



controlling the rate of injection of either holes or electrons, or both, by varying the hole and/or injection control voltages 18, 20.

**[0031]** The electroluminescent device 100 thus provides three independent controls: control of electroluminescence intensity through the electroluminescence voltage 22, control of hole injection current through the hole injection control voltage 18 and control of electron injection current through the electron injection control voltage 20. Hence, efficiency of the electroluminescent device 100 may be optimized by setting the injection voltages 18, 20 to provide balanced hole and electron injection independently of control of electroluminescence intensity. Improved efficiency may also be obtained by keeping high injection E-fields away from the recombination region 13 to minimize leakage currents.

**[0032]** Electroluminescence produced by the device 100 may be coupled out either the top or bottom of the device. In another embodiment of the electroluminescent device, the field effect gate structures (hole injection control gate 144 and hole injection control gate insulator layer 146, and/or electron injection control gate 164 and electron injection control gate insulator layer 166) may be fabricated of a transparent material. For example, the hole injection control gate 144, or electron injection control gate 164, or both, may be formed from materials such as  $\text{In}_2\text{O}_3$ ,  $\text{SnO}_2$ , and  $\text{ZnO}$  doped with the appropriate impurities so as to attain high conductivity.

**[0033]** FIG. 5 provides an alternate embodiment of an electroluminescent device, indicated generally at 300, in accordance with the present invention. The hole injection region 142 includes a hole injector contact 242 and a hole injector layer 248. The electron injection region 162 includes an electron injector contact 262 and an electron injector layer 268. A single gate insulator 156 spans a bottom surface of the inorganic phosphor 12 to provide both the hole and electron injection control gate insulator 146, 166, respectively.

**[0034]** The hole and electron injector layers 248, 268 may be formed of the same material as the inorganic phosphor 12 to facilitate flow of carriers from the injector layers 248, 268 into the inorganic phosphor 12. A reduced thickness of the injector layers 248, 268 relative to the inorganic phosphor 12 allows lower

injection control voltages 18, 20. Optionally, the injector layers 248, 268 may also be doped to reduce the hole and electron injection barriers to improve carrier injection according to another embodiment of the invention.

[0035] In yet another embodiment of the electroluminescent device 300 of FIG. 5, it is desirable that a portion of the hole and electron injection control gates 144, 164 extends past the injector layers 248, 268 so they are opposite the inorganic phosphor 12 and separated by gate insulator 156. This helps to ensure that the accumulation regions extend into the inorganic phosphor 12. Otherwise, poor injection efficiency may result due to trapping of carriers within the injection layers 248, 268. In another embodiment of the present invention, the hole injector contact 242 and the electron injector contact 262 may be extended to completely cover the hole injector layer 248 and the electron injector layer 268, respectively. In still another embodiment of the present invention, the hole injector contact 242 and electron injector contact 262 may also be extended to partially cover the inorganic phosphor 12.

[0036] FIG. 6 provides a further embodiment of an electroluminescent device, indicated generally at 400, in accordance with the present invention. In the electroluminescent device 400 of FIG. 6, the relative orientation of the electron injection structure 16 and the hole injection structure 14 has been changed relative to the embodiment illustrated in FIG. 2 to place the hole injection control gate 144 and electron injection control gate 164 on opposite sides of the inorganic phosphor 12. In another embodiment, the hole injection control gate 144 and electron injection control gate 164 may be extended, as shown in FIG. 6, so that they are partially opposite each other on opposite sides of the inorganic phosphor 12. Electroluminescent device 400 may allow improved efficiency, since drift of carriers can take place both laterally and vertically within the inorganic phosphor 12, rather than just through a surface layer as in the embodiments illustrated in FIGS. 2 and 5. For example, holes may drift from an accumulation layer 124 in directions 402 and 404. Electrons may drift from an accumulation layer 126 in directions 406 and 408. Hence, the recombination region 13 may occupy most of the inorganic phosphor 12.

**[0037]** A plurality of the electroluminescent devices described above may be used to implement a display. For example, FIG. 7 illustrates a schematic diagram of a display, shown generally at 500, implemented using a plurality of the electroluminescent devices 10 of FIG. 1. The electroluminescent devices 10 may be arranged in a matrix, with the anodes 24 tied to a common anode voltage bus 502, and the cathodes 26 tied to a common cathode voltage bus 504. The electron injection control gate 36 may be tied to a common electron injection control gate bias bus 506 and the hole injection control gate 34 may be used to control individual pixels 510. Individual pixels 510 may be controlled by row and column addressing, using a row (select) line 512 and a column (data) line 514. When an individual pixel 510 is selected, a transistor 516 is turned on to apply an appropriate hole injection control voltage. A capacitor 518 may be included to provide storage of the hole injection control voltage when sequential scanning of individual pixels is performed. The capacitor 518 may also be used to compensate for persistence.

**[0038]** According to an alternative embodiment of a display, the hole injection control gate 24 may be tied to a common hole injection control gate bias bus and the electron injection control gate 34 may be used to control the pixel 510.

**[0039]** An embodiment of a method 800 of fabrication of an electroluminescent device consistent with the present invention is now described. Although the fabrication of a single electroluminescent device is described, it is to be understood that an array or plurality of electroluminescent devices, for example a display, may be fabricated simultaneously using the same process.

**[0040]** Referring to FIG. 8, the method 800 may include forming 802 a first part of a hole injection structure. The method 800 may further include forming 804 a first part of an electron injection structure separated from the first part of the hole injection structure. The method 800 may further include depositing 806 an inorganic phosphor layer spanning an area between and at least partially overlapping the first part of the hole injection structure and the first part of the electron injection structure. The method 800 may further include forming 808 a second part of the hole injection structure in contact with the

inorganic phosphor layer substantially opposite the first part of the hole injection structure. Finally, the method 800 may further include forming 810 a second part of the electron injection structure in contact with the inorganic phosphor layer substantially opposite the first part of the electron injection structure and  
5 separated from the hole injection structure.

**[0041]** According to another method embodiment, the electroluminescent device may be fabricated on a substrate, by forming the first part of the hole injection structure on a substrate and forming the first part of the electron injection structure on a substrate. The substrate may be selected to be  
10 a transparent material, for example, glass. Alternately, the substrate may be selected to be an opaque material, for example, silicon. Light may be operationally coupled out either the top, or the bottom, of the electroluminescent device. As will occur to one skilled in the art, it may be desirable to fabricate some layers, for example, the gate electrodes or injection regions, from a  
15 transparent material to allow transmission of light through those layers.

**[0042]** The electroluminescent device layers may be fabricated in a variety of orders. According to one alternate method embodiment, forming the first part of the hole injection structure may include forming a hole gate electrode layer and forming an insulator layer at least covering the hole gate electrode.  
20 Forming the second part of the hole injection structure may include forming a hole injection layer in contact with the inorganic phosphor and substantially opposite the first part of the hole injection structure.

**[0043]** According to another alternate method embodiment, forming the first part of the hole injection structure may include forming a hole injection layer.  
25 Forming the second part of the hole injection structure may include forming an insulator layer on the inorganic phosphor layer substantially opposite the first part of the hole injection structure. Forming the second part of the hole injection structure may further include forming a hole gate electrode layer on the insulator layer substantially opposite the first part of the hole injection structure.

30 **[0044]** Similarly, fabrication of the electron injecting structure layers may also be performed in a variety of orders. According to another alternate method embodiment, forming the first part of the electron injection structure may include

forming an electron gate electrode layer and forming an insulator layer at least covering the electron gate electrode. Forming the second part of the electron injection structure may include forming an electron injection layer in contact with the inorganic phosphor and substantially opposite the first part of the electron

5 injection structure. And, finally, according to another alternate method embodiment, forming the first part of the electron injection structure may include forming an electron injection layer. Forming the second part of the electron injection structure may include forming an insulator layer on the inorganic phosphor layer substantially opposite the first part of the electron injection  
10 structure. Forming the second part of the electron injection structure may further include forming an electron gate electrode layer on the insulator layer substantially opposite the first part of the hole injection structure.

**[0045]** Forming the first part of the hole injection structure and forming the first part of the electron injection structure may be performed simultaneously.  
15 Forming the second part of the hole injection structure and forming the second part of the electron injection structure may also be performed simultaneously. Finally, the various steps of forming an insulator layer may be performed simultaneously.

**[0046]** Flexibility in the fabrication of the electroluminescent device 100  
20 may be obtained by the separate control of hole and electron injection. Since independent operational control of the hole and electron injection currents is provided by the controllable hole injection structure 14 and the controllable electron injection structure 16, the injection properties of the controllable hole injection structure 14 need not be precisely matched to the controllable electron  
25 injection structure 16. Imbalances can be adjusted at operation time by adjusting the hole and electron injection control voltages 18, 20 to achieve balanced and efficient injection.

**[0047]** It is to be understood that the above-referenced arrangements are illustrative of the application for the principles of the present invention.

30 Numerous modifications and alternative arrangements can be devised without departing from the spirit and scope of the present invention. While the present invention has been shown in the drawings and described above in connection